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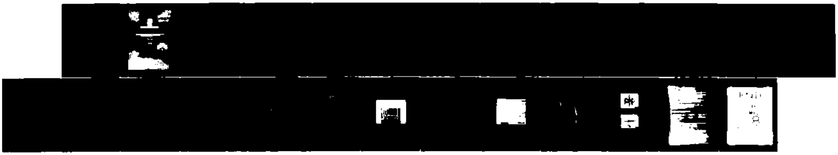

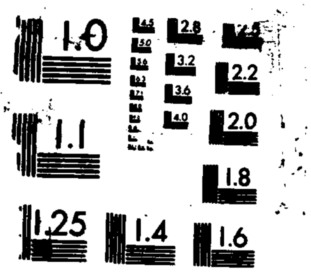

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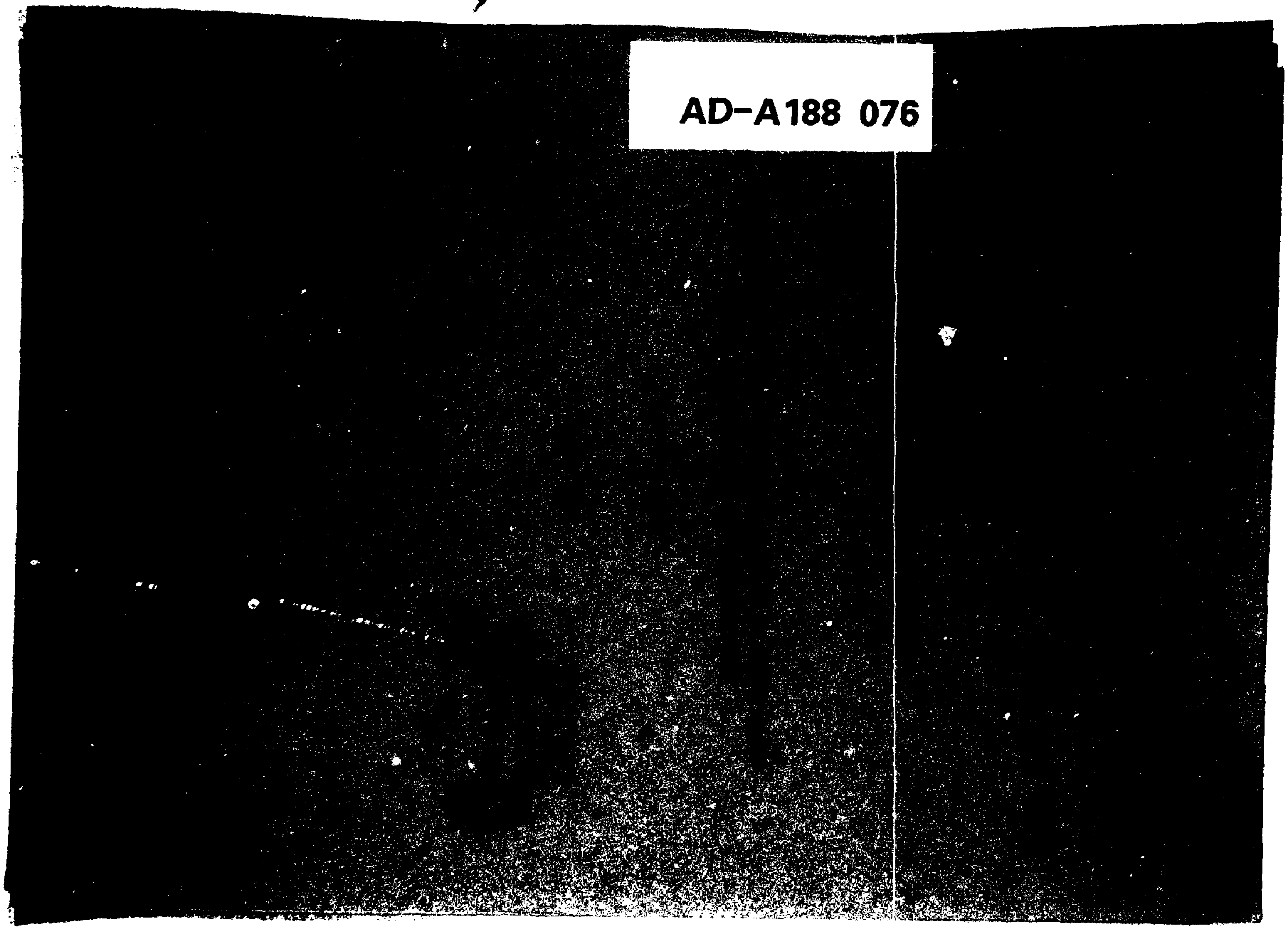

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MEASUREMENTS OF THE OUT-OF-PLANE DISPLACEMENT OF AN AXIALLY LOADED CRACKED METAL SHEET WITH A CFRP REPAIR PATCH

by

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SUMMARY

An adhesively bonded carbon fibre reinforced plastic (CFRP) repair patch situated centrally on one face of a 1.6mm thick sheet test piece of aluminium alloy 7475-T761 containing a central fatigue crack caused an out-of-plane displacement when the test piece was loaded in tension normal to the crack length.

Out-of-plane displacements for two crack lengths (2a = 75 mm and 2a = 94 mm) were measured using a dial gauge. The magnitude of the displacement depended upon crack length and was a nonlinear function of applied load. A greater displacement per load increment occurred at low loads and there was a tendency towards a limiting value at high loads. A moiré shadow technique was also used to measure displacements and the results agreed well with dial gauge measurements.

Ultrasonic C-scan images revealed an adhesive debond region near the crack line at the centre of a crack of length 2a = 94 mm. This debond is thought to be the reason for a disparity observed between displacement measurements on the patched and unpatched surfaces of the test piece.

LIST OF CONTENTS

		Page
1	INTRODUCTION	3
2	EXPERIMENTAL DETAILS	3
	2.1 Materials	3
	2.2 Measurement of displacement	4
	2.2.1 Dial gauge technique	4
	2.2.2 Shadow moiré technique	4
3	RESULTS	5
	3.1 Displacement results	5
	3.1.1 Contour and isometric plots	5
	3.2 Shadow moiré results	6
4	DISCUSSION	6
5	CONCLUSIONS	7
Acknowledgments		7
Tables 1 and 2		8
References		9
Illustrations		Figures 1-13
Report documentation page		inside back cover

1 INTRODUCTION

A technique for the repair of a fatigue-cracked metal sheet using an adhesively bonded patch of CFRP laminate has been reported previously[1], and a comprehensive review of repair patching has been published[2].

During the course of earlier work[1] using 1.6mm thick aluminium alloy sheet, an out-of-plane displacement or 'neutral axis offset' was observed caused by the asymmetric loading arrangement of a single patch on one face of the cracked sheet. Other workers have subsequently reported a similar observation[3,4]. The patching of one face of a cracked panel rather than both faces is envisaged to be an often encountered situation in the practical application of repair patching, *eg* where only one face of a cracked panel is accessible for repair. Since no quantitative data on the neutral axis offset were available, measurements of displacement were made on an aluminium alloy sheet patched on one side. Parameters studied included the gross applied stress, the crack length, and the integrity of the patch to panel adhesive bond.

2 EXPERIMENTAL DETAILS

2.1 Materials

A 1.62mm thick sheet of clad aluminium alloy 7475-T761 was used. The cladding thickness was 0.25 ± 0.05 mm. The 150mm wide by 380mm long panel test piece contained a central spark-machined crack starter slot 10mm × 0.5mm. The panel was designated 3/19.

The carbon fibre reinforced plastic (CFRP) laminate patch was made from a five-shaft satin cloth woven from Courtaulds XAS carbon fibre, 1.2 denier filament in tows of 3000 fibres. The cloth was impregnated with a solution of epoxy-hardened, hot setting Friedel-Crafts resin, Xylok 237. After air drying the plies were hot moulded at a temperature of 453 K and pressure of 3 MPa to produce a four-ply laminate with a 0, 90° lay-up. The mechanical properties of the laminate were determined from a testpiece 10 mm wide by 165 mm long with bonded aluminium end plates of dimensions 10mm × 50mm × 1.25mm. The free length of testpiece between the end plates was 65 mm. At a loading rate of 0.02 mm/min on a 20 mm gauge length, the tensile Young's modulus (E) was determined as 63.5 GPa. The repair patch was 1.02 mm in thickness and measured 102.4mm × 83.7mm.

Prior to patching, a fatigue crack was grown in the panel under a constant amplitude sinusoidal loading waveform at a frequency of 10 Hz. The maximum gross fatigue stress was 60 MPa and the R-ratio (min/max stress) was 0.1. The load amplitude was constant (ΔK increasing) and the fatigue crack was grown to a length of $2a = 75$ mm, ($2a/2W = 0.5$).

The repair patch was bonded to the aluminium alloy panel using Hysol 9309 epoxy adhesive. The aluminium alloy sheet surface was prepared by abrading with carborundum paper and water then rinsed with acetone and dried. A uniform adhesive layer thickness was achieved by the use of 0.156mm diameter nylon filament spacers. The patch was bonded at room temperature under a pressure of 0.1 MPa for 5 days. Typical mechanical properties of this adhesive are a shear modulus (G) of 0.7 GPa and tensile Young's modulus (E) of 2.4 GPa (manufacturer's data).

2.2 Measurement of displacement

2.2.1 Dial gauge technique

The repair patched panel was sprayed with silver paint and a grid drawn on both faces in pencil as shown in Fig 1. The panel was loaded via pins in a servohydraulic test machine and a dial gauge was mounted on the lower grip using a magnetic clamp and extension mounting bars. The technique found most satisfactory for obtaining a consistent zero displacement baseline was to zero the dial gauge under a load of 0.5 kN. Measurements of displacement at increasing load values were made with 0.5 kN load increments.

In order to determine the shape of the panel and patch under load, point measurements of displacement were made on the 10mm square grid at the maximum load value of 14.7 kN (60 MPa gross stress). Measurements were made over one quadrant of each side of the panel. The load was reduced to 0.5 kN between each reading, the gauge zeroed, and the load reapplied. Three readings were averaged for each point displacement value. The reproducibility was generally better than 0.02 mm.

On completion of measurement, the panel was subjected to further fatigue loading in order to grow the fatigue crack. The panel was subjected to 186630 load cycles as for the pre-crack described in section 2.1 and the test stopped at a crack length of 2a = 94.2 mm (2a/2W = 0.62). Asymmetrical crack growth was observed, where LHS a = 49.8 mm and RHS a = 44.4 mm.

Further displacement measurements were carried out at the new value of crack length as described above.

2.2.2 Shadow moiré technique

A comparison of displacement measurements obtained by the dial gauge (contact) method and shadow moiré (non-contact) method[5] was carried out at the crack length value of 2a = 94 mm. The panel was first sprayed with white gloss paint to provide a reflective surface. A glass diffraction grating of line spacing 0.125 mm was placed on the repair patched side of the panel resting on three 5mm steel balls. Clips and rubber bands were used to secure the grating, and the panel was inserted in a tensile test machine using the same attachments. A white light source with a parallel beam was positioned at 45° incidence angle to the panel, and a camera stationed at 90° to the panel surface, as illustrated in Fig 2. The panel was loaded to 14.7 kN and a photograph was taken of the moiré fringes resulting from the panel and patch surface displacements. The photograph was analysed to plot values of displacement from the fringe pattern, where in this arrangement the fringe-to-fringe spacing represented a displacement difference of 0.125 mm.

3 RESULTS

3.1 Displacement results

A plot of lateral displacement against load is shown in Fig 3 at two positions on the CFRP patch for a panel crack length of 2a = 75 mm. The displacement is seen to be a nonlinear function of load, and non-uniform over the patch surface. A relatively small increment of tensile load resulted in a relatively large displacement increment at low load values. The displacement tended towards a limiting value at high loads.

A similar plot of lateral displacement against load is shown in Fig 4 for two values of panel crack length showing displacement at the centre of the patch. The displacement at maximum load was greater for the longer crack length of 2a = 94 mm compared to the crack length of 2a = 75 mm. At load values of less than 4.5 kN, the trend was reversed to a small extent, with greater displacements for the shorter crack length, and this observation will be discussed more fully later.

A comparison of displacement measurements at the centre of the patched and unpatched sides of the panel is shown in Fig 5. The crack length was 2a = 94 mm and the differences between loading and unloading on displacement were negligible (curve A). A considerable disparity was, however, observed between measurements taken on the two sides of the panel. At maximum load, the unpatched side of the panel was displaced by 1.55 mm compared to 1.25 mm measured on the patch surface. This disparity will be discussed later.

3.1.1 Contour and isometric plots

A contour plot of the unpatched side of the panel with crack length 2a = 75 mm is shown in Fig 6. The plot was generated by an interpolation algorithm called PLOTSURF on an ICL 1906S mainframe computer, using point displacement values measured over one quadrant of the panel. To aid visual appreciation the contours have been reflected in the X and Y axes. The relative position of the CFRP patch on the opposite side of the panel has been indicated by the dashed line P .

A contour plot and isometric plot for displacements of the patch surface are shown in Fig 7a&b. The isometric plot of Fig 7b was generated from data from one quadrant, reflected in the X and Y axes as above, and gives a visual appreciation of the patch surface topography.

The plots illustrate the sense of displacement caused by the neutral axis offset in that the patched side of the panel is offset towards the neutral axis. The contour and isometric plots for the central region of the patch surface are shown in Fig 8a&b, generated from displacement measurements on a 5mm square grid spacing. The complexity of patch surface deformation is evident.

3.2 Shadow moiré results

A photograph of the moiré fringe pattern observed on the patched side of the loaded panel is shown in Fig 9. The crack length was 2a = 94 mm, with LHS a = 49.8 mm, RHS a = 44.4 mm. The asymmetry of crack length may be responsible for the asymmetry in the fringe pattern.

Displacement values measured from the moiré interference fringe pattern are shown in Fig 10 at three positions along the patch: x = − 35 mm; x = 0; x = + 35 mm. The results are compared with displacement values measured using the dial gauge technique, and the plots show good agreement.

3.3 Examination of fracture surface

Observation of the aluminium panel fracture surfaces revealed an asymmetric fatigue crack front, as shown in Fig 11. This observation has been noted elsewhere[3,4,6] and indicates that the distribution of crack tip stresses across the crack front is modified by the superimposed out-of-plane displacement. The crack front region near the unpatched face of the panel showed a longer effective crack length, indicating a local increase in crack tip stress intensity factor range.

4 DISCUSSION

The results have shown that a patched, cracked sheet suffers a neutral axis offset when the crack is loaded, confirming the observations of other workers[3,4]. Quantitative data has been presented which indicates that for the panel, adhesive, patch, and loading conditions considered, the maximum displacement measured was approximately 1 to 1.5 mm. The displacement effect is illustrated in Fig 12. As the axial load is increased, load is transferred to the patch and a displacement results as the loading line attempts to establish a straight path through the asymmetric structure. This effective straightening of the load path produces the expected result of high deflection at low loads and a limiting value of displacement as load is increased. Hence displacement was a nonlinear function of load, and varied over the surface of the patch.

A disparity was observed in one situation as shown in Fig 5 between the displacements measured on the patched side of the panel and the unpatched side. The crack length was 2a = 94 mm, and the difference in displacement on opposite sides of the panel at the centre of the crack was 0.3 mm, suggesting that the panel was separating from the patch, or that some void was being created. An ultrasonic C-scan image was taken of the unloaded panel immediately after application of the patch for a crack length of 2a = 75 mm, and this was compared with a C-scan taken of the unloaded panel for a crack length of 2a = 94 mm, as shown in Fig 13a&b.

At the longer crack length an extensive debond region was observed along the line of the crack, strongly suggesting that the displacement disparity of 0.3 mm was caused by the debond region opening under load. It is thought that the panel is pulling away from the patch along the crack line and if so, then this 'splaying' of the crack edges is akin to the buckling observed in an unpatched centre-cracked sheet highly loaded in tension. Since it is known that high shear stresses exist in the adhesive between the patch and panel along the line of the crack[4], then the additional stresses in the adhesive due to the buckling condition are thought to be contributory to the formation of an adhesive debond by increasing interfacial stresses. A comparison of the load-displacement curves for two crack length values as shown in Fig 4 indicates that the presence of a debond region also affects the magnitude of patch displacement under load. The higher overall displacement at high loads for the longer crack would be expected as a result of both the reduced stiffness of the aluminium panel with a longer crack and the reduced constraint on panel displacement because of the increase in debond area. The 'crossover' effect at low loads may be explained by the presence of the debond at the longer crack length; since the debond occurs where adhesive shear stresses and hence load transfer to the patch are greatest, removal of this region would be expected to result in reduced load transfer to the patch at low loads, hence little displacement. It is seen, therefore, that load transfer to the patch is synonymous with displacement and *vice versa* . If no load transfer occurred, no displacement would be observed. At low axial load in particular, the out-of-plane displacement is a sensitive function of load transfer to the patch - the more effective the transfer of load, the greater the displacement.

By these arguments, fatigue loading a patched panel with no out-of-plane displacement could result in the suppression of adhesive debond formation, and this will be investigated in future work. These results strongly suggest, therefore, that out-of-plane displacement is a contributory factor to the formation of an adhesive debond.

A further effect of displacement is the modification of the crack tip stress intensity factor range along the crack tip. The crack tip stress intensity factor range is higher near the non-patched side of the panel resulting in a higher local crack growth rate. This effect is caused by the neutral axis offset, which has been analysed[4,6] and it has been shown[4] that the crack growth rate is increased near the unpatched side of the panel.

The important practical inference of this work is that out-of-plane displacement may reduce the patch effectiveness both by promoting the formation of a debond, the presence of which will reduce load transfer to the patch, and also by modifying the crack tip stress intensity distribution along the crack front.

5 CONCLUSIONS

Loading a fatigue crack in a thin metal sheet having a bonded woven CFRP patch resulted in an out-of-plane displacement the magnitude of which was dependent on crack length and applied load. Displacement of the unpatched face of the panel was influenced by adhesive debond between the patch and panel, the presence of which resulted in an increase in displacement.

Acknowledgments

Mr R.F. Mousley, Materials and Structures Department, RAE, produced the shadow moiré image and Mr D.P. Vick, Instrumentation and Trials Dept, RAE produced the contour and isometric plots.

Table 1

DISPLACEMENT MEASUREMENTS OF UNPATCHED SURFACE OF PANEL, 2a = 75 mm UNDER A LOAD OF 14.7 kN

		X-axis co-ordinate (mm)							
		0	10	20	30	40	50	60	70
Y-axis co-ordinate (mm)	0	1.140*	0.989	0.976	0.968	0.924	0.954	0.931	0.970
	10	1.054	0.886	0.885	0.900	0.904	0.928	0.951	0.930
	20	0.926	0.811	0.861	0.842	0.868	0.892	0.920	0.920
	30	0.830	0.722	0.753	0.795	0.817	0.844	0.835	0.880
	40	0.726	0.614	0.651	0.700	0.758	0.759	0.781	0.830
	50	0.630	0.541	0.560	0.632	0.655	0.680	0.712	0.768
	60	0.561	0.483	0.505	0.548	0.579	0.620	0.658	0.709
	70	0.538	0.423	0.445	0.476	0.549	0.572	0.571	0.620
	80	0.478	0.378	0.396	0.437	0.470	0.502	0.520	0.555
	90	0.360	0.350	0.360	0.390	0.415	0.440	0.544	0.471
	100	0.267	0.283	0.310	0.338	0.360	0.381	0.381	0.406

*Estimate
Displacements are away from the loading axis, *ie* convex surface

Table 2

DISPLACEMENT MEASUREMENTS OF PATCH SURFACE, 2a = 75 mm UNDER A LOAD OF 14.7 kN

		X-axis co-ordinate (mm)								
		0	5	10	15	20	25	30	35	40
Y-axis co-ordinate (mm)	0	1.109	1.102	1.090	1.079	1.069	1.066	1.062	1.055	1.055
	5	1.092	1.088	1.082	1.017	1.028	1.020	1.053	1.058	1.054
	10	1.039	1.034	1.029	1.005	1.00	0.987	1.025	1.025	1.02
	0	1.109		1.090		1.069		1.062		1.055
	10	1.039		1.029		1.00		1.025		1.02
	20	0.925		0.946		0.935		0.958		0.949
	30	0.842		0.851		0.848		0.849		0.855
	40	0.743		0.755		0.744		0.766		0.783

Displacements are towards the loading axis, *ie* concave surface

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No.	Author	Title, etc
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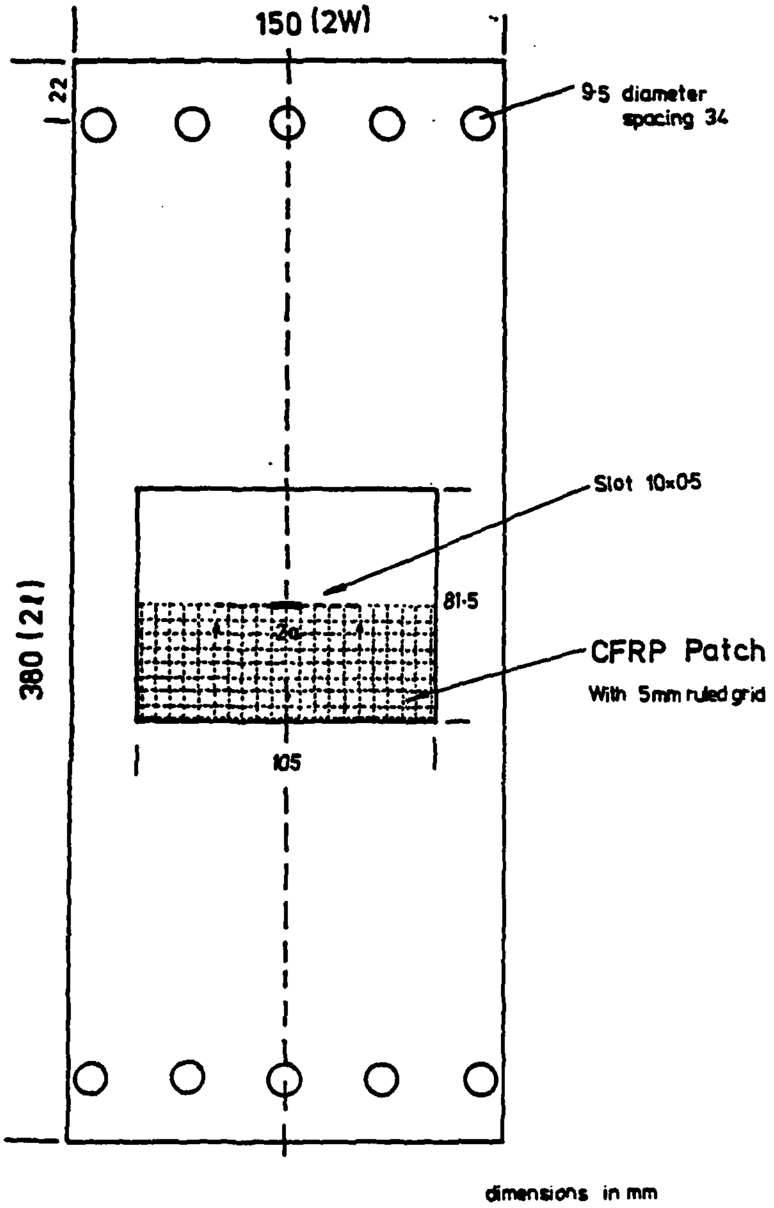
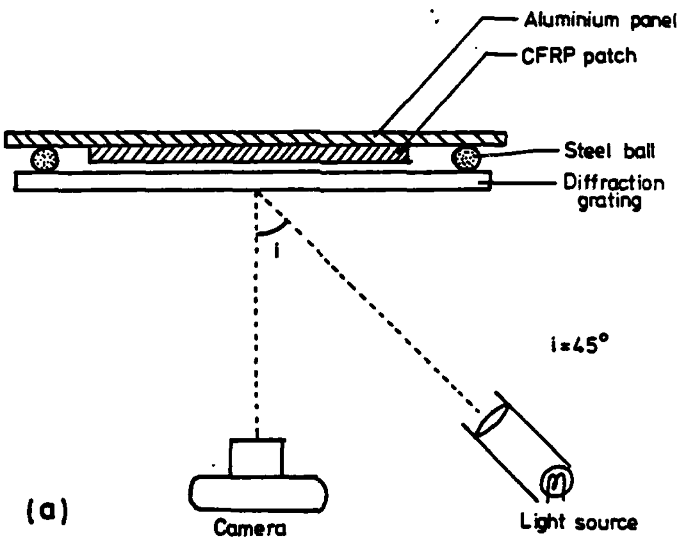


Fig 1 Dimensions of aluminium alloy panel and CFRP patch

Fig 2



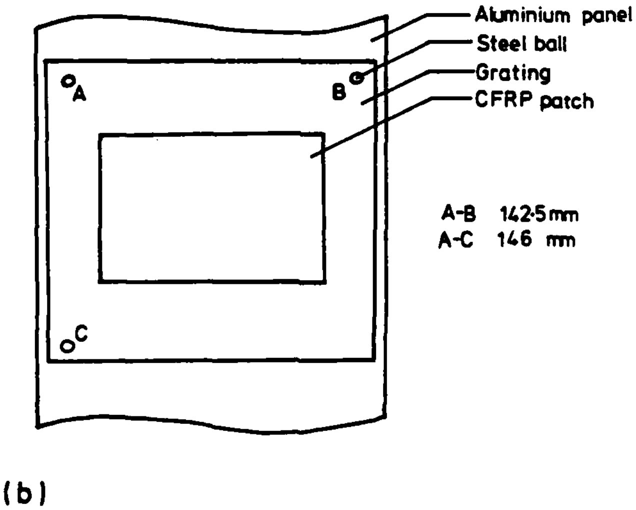


Fig 2 Illustration of the shadow moiré technique shown in (a) plan view and (b) front view

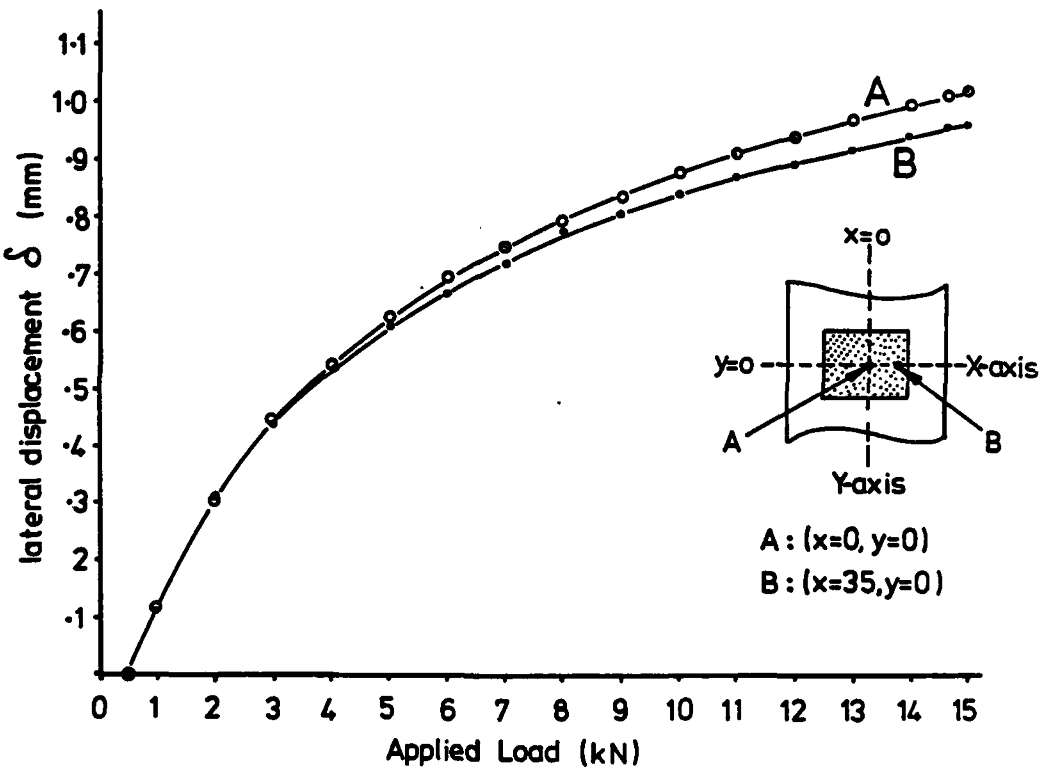


Fig 3 Effect of applied load on patch surface displacement at two positions A,B on the patch surface with a panel crack length of 2a = 75 mm

Fig 4

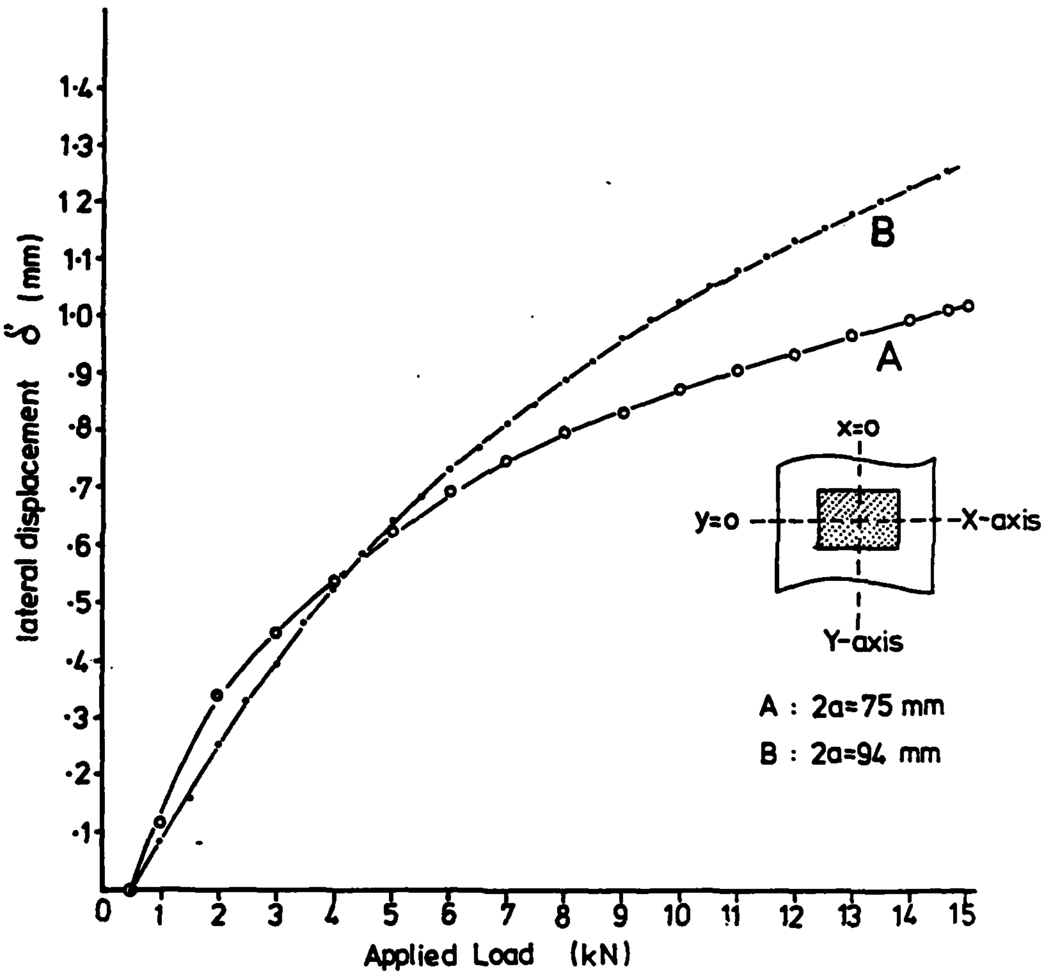


Fig 4 Effect of applied load on lateral displacement at the centre of the patch (x = 0, y = 0) for two values of panel crack length

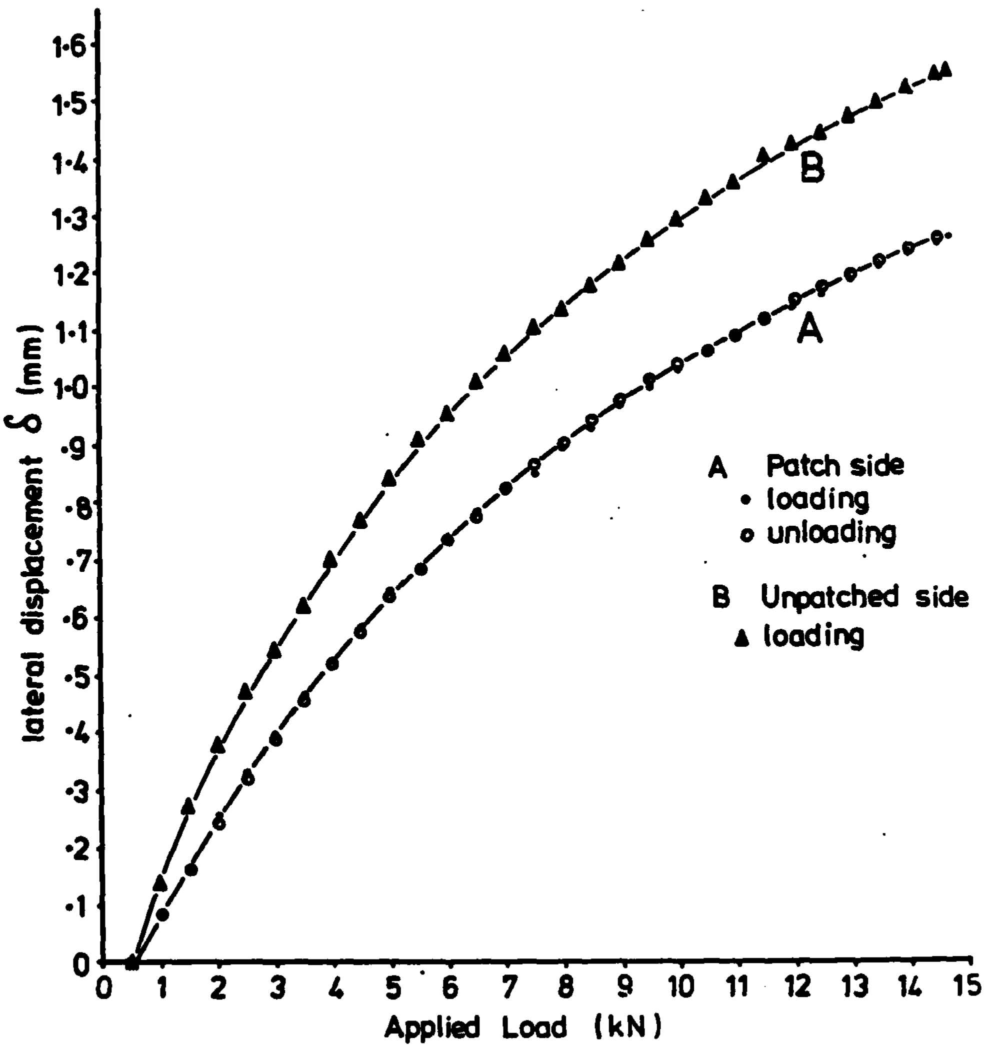


Fig 5 Displacement measurements at the centre (x = 0, y = 0) of a panel with a crack length of 2a = 94 mm (loading and unloading) A patch side and B unpatched side

Fig 6

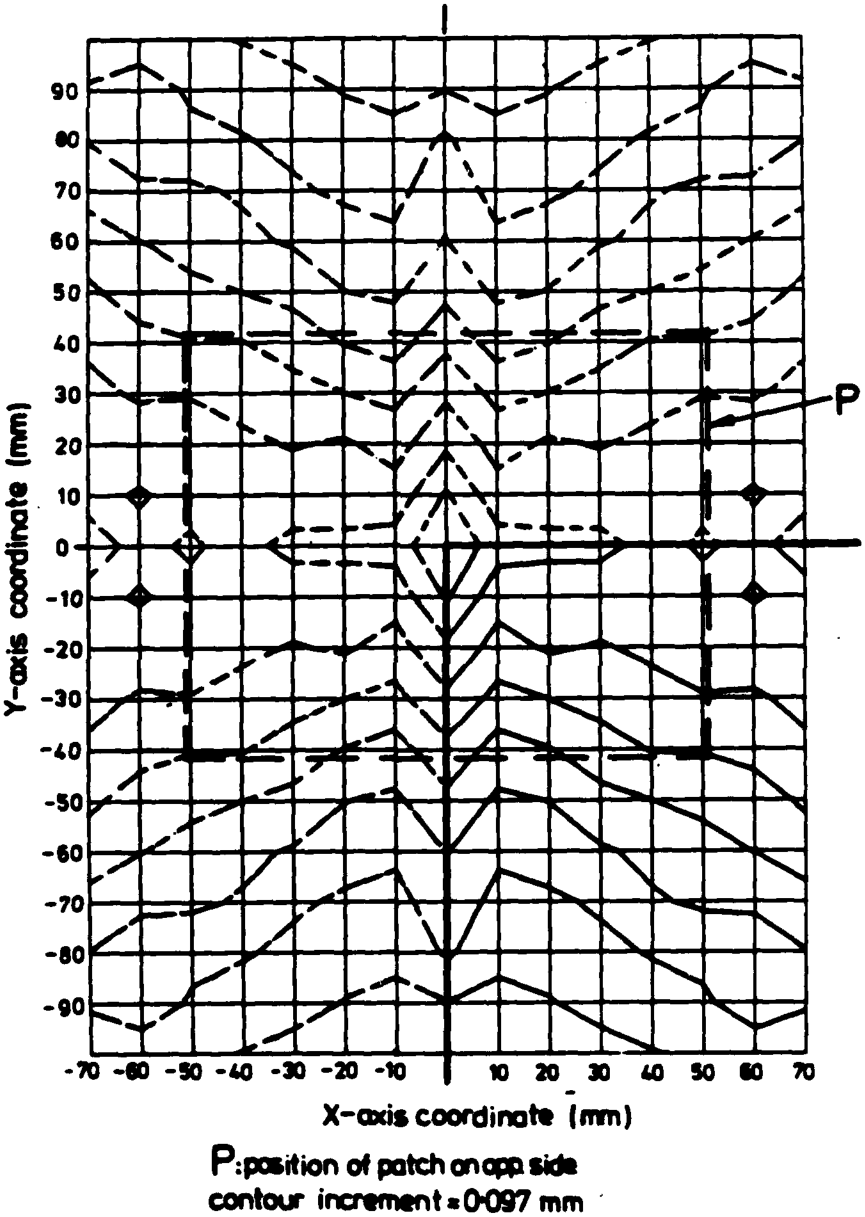


Fig 6 Displacement contour plot of the unpatched side of panel 3/19 with a crack length of 2a = 75 mm. (Measurements from one quadrant reflected in X and Y axes.)

Fig 7a&b

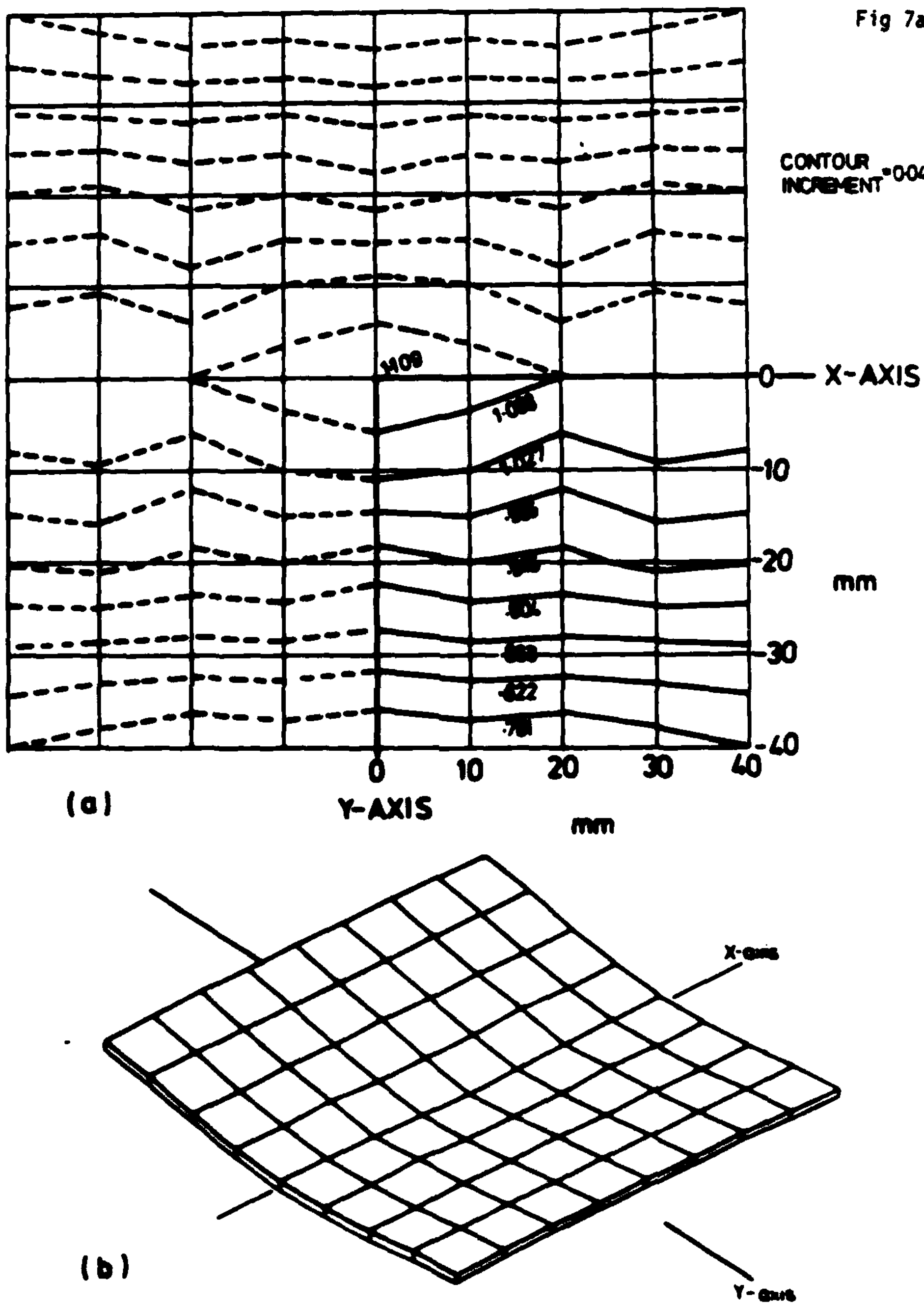
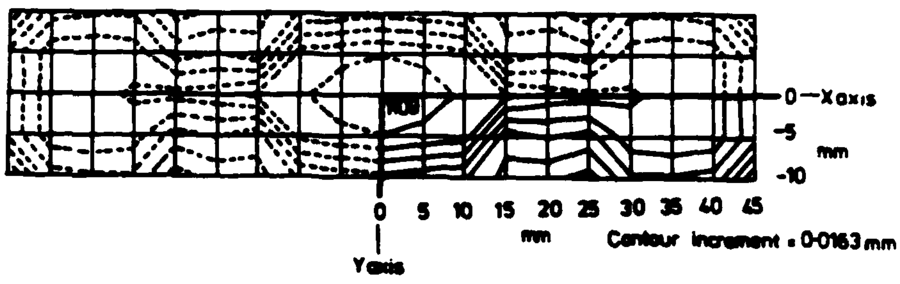
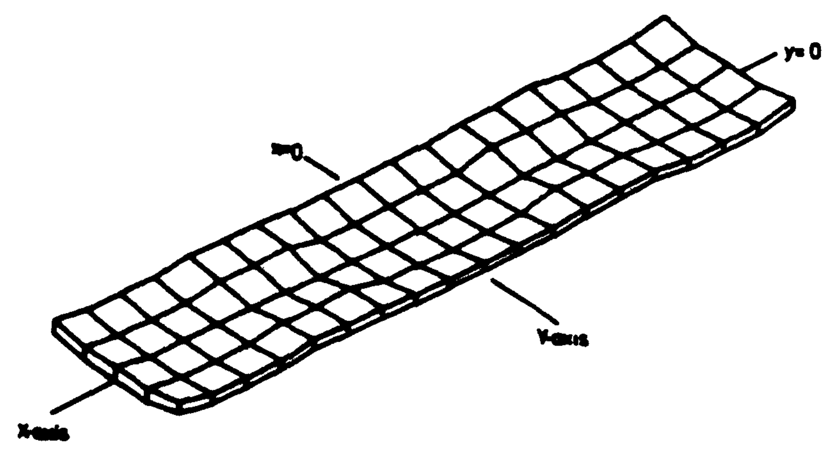


Fig 7 Displacements of patch surface for a panel crack length of 2a = 75 mm. Measurements from one quadrant reflected in X and Y axes
(a) contour plot (b) isometric plot

Fig 8a&b



(a)



(b)

Fig 8 Displacement of central patch region for a panel crack length of 2a = 75 mm. Measurements from one quadrant reflected in X and Y axes (a) contour plot (b) isometric plot

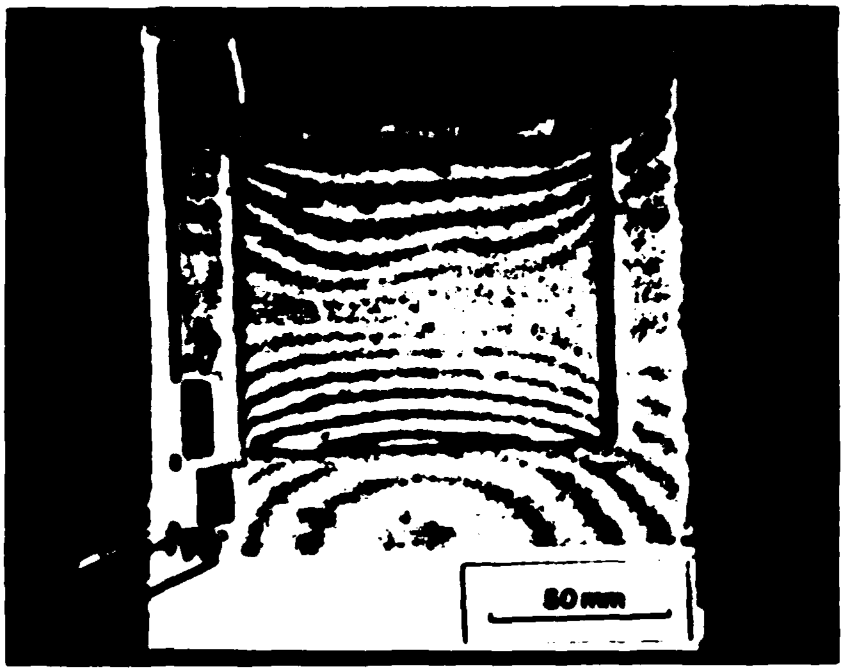


Fig 9 Fringes on patched side of panel 3/19 under tensile load observed by the shadow Moiré technique. Crack length 2a = 94 mm

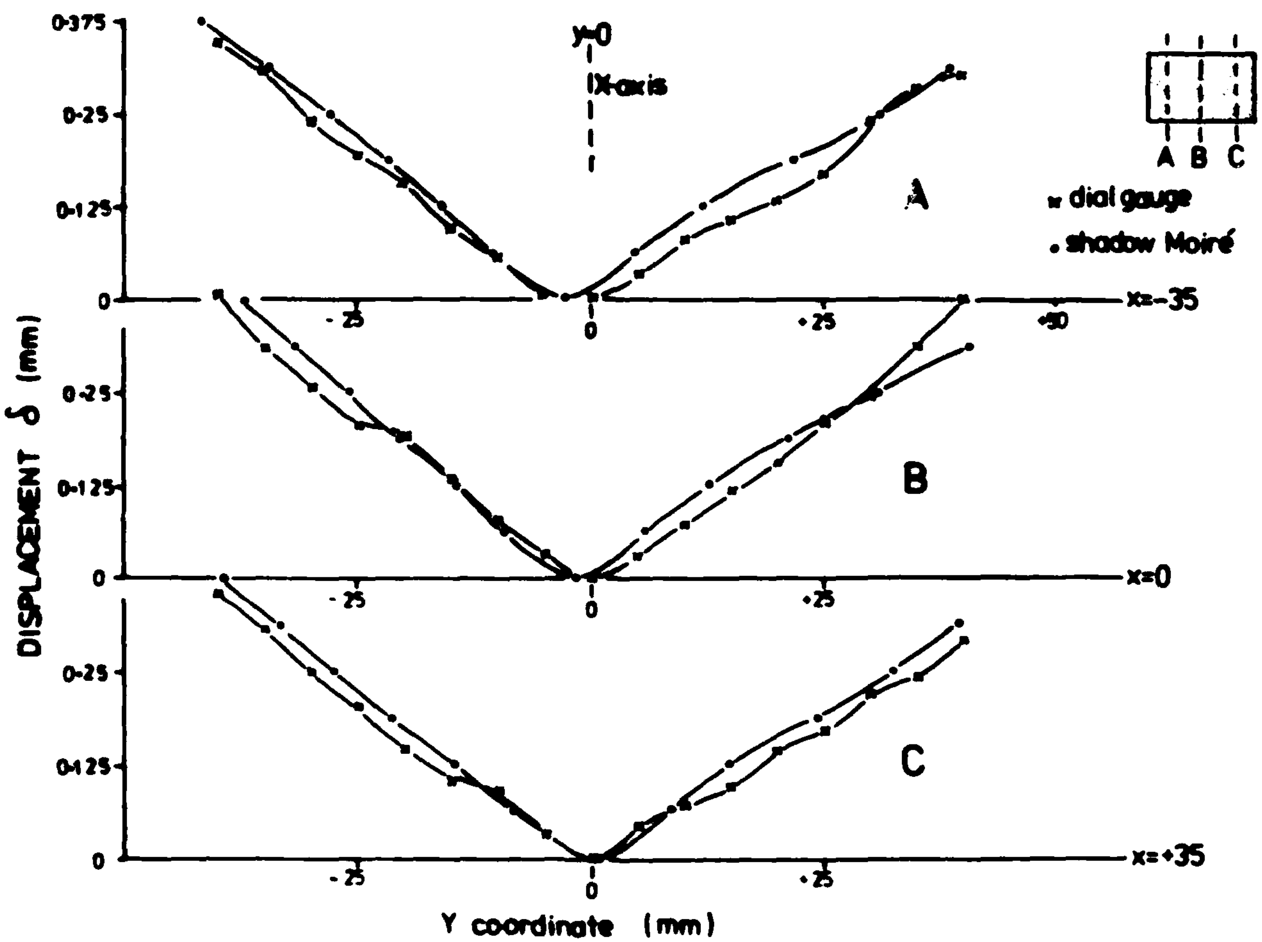


Fig 10 Comparison of patch displacement profiles measured by dial gauge and shadow Moiré techniques, where panel crack length, 2a = 94 mm.

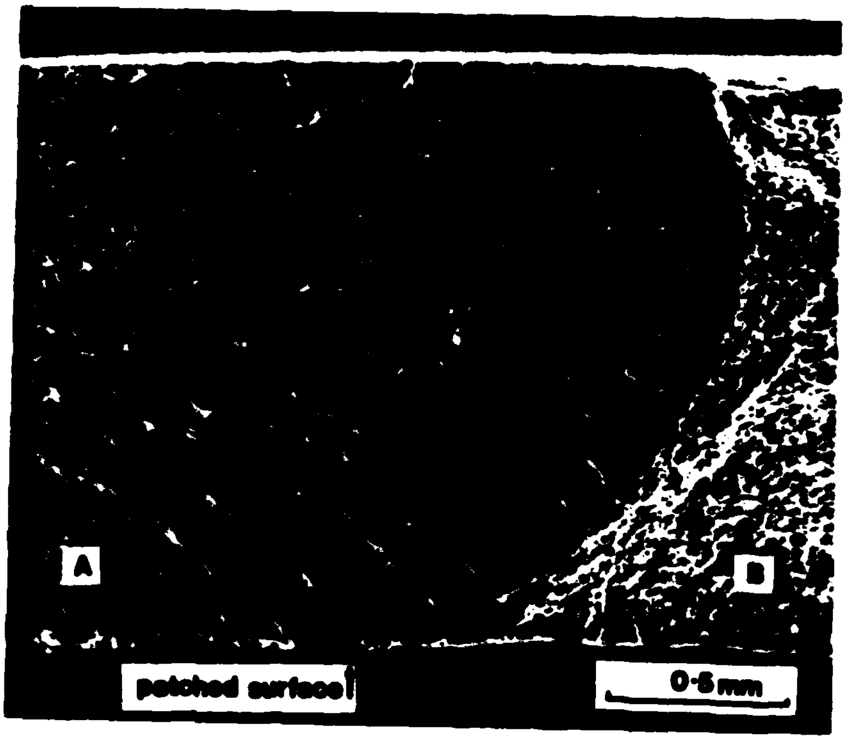


Fig 11 Scanning electron micrograph of fatigue fracture surface on aluminium panel showing the asymmetric crack front shape of fatigue crack (A) at onset of final tensile failure mode (B)

Fig 12

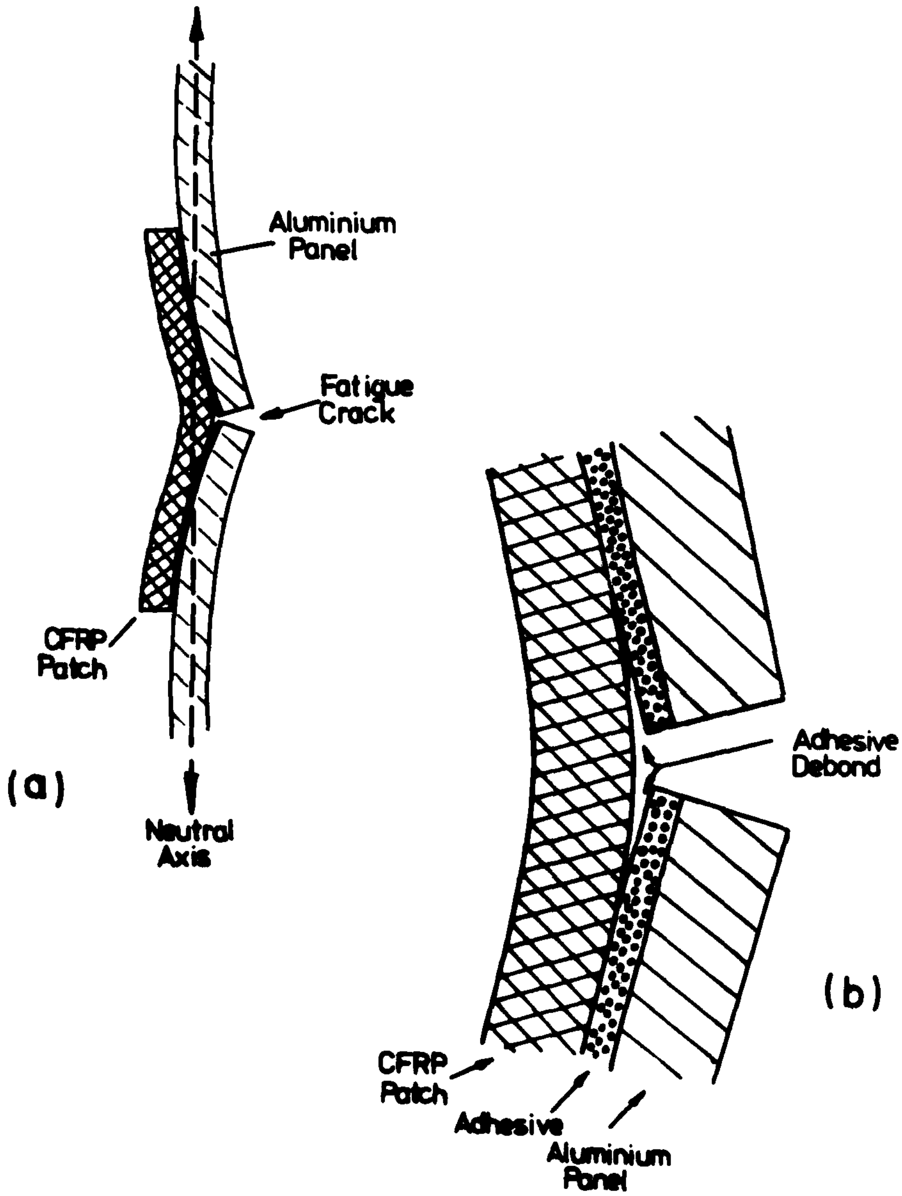
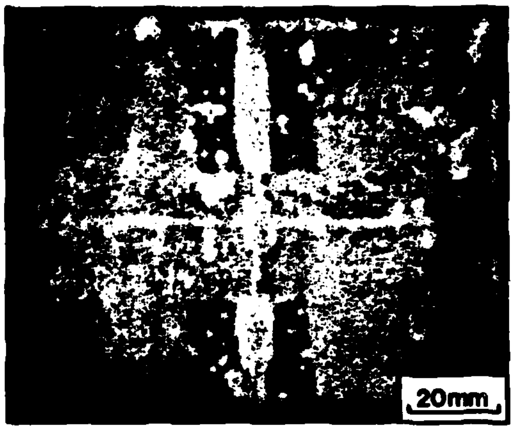
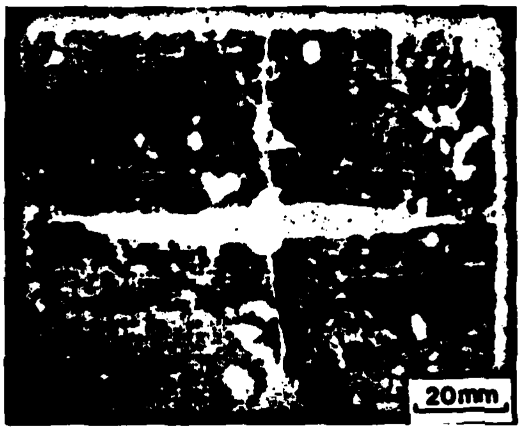


Fig 12 Illustrations of out-of-plane displacement showing
(a) offset due to modification of neutral axis and
(b) effect of debond on panel displacement



(a)



(b)

Fig 13 Ultrasonic C-scan images of the CFRP patch region for two values of panel crack length (a) 2a = 75 mm (b) 2a = 94 mm

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